GROWING JUPITER'S CORE BY RUNAWAY ACCRETION; S.J. Weidenschilling (PSI/SJI)

The origin of the gas giant planets, Jupiter and Saturn, is a vexing problem for cosmogonists. The currently most accepted concept of their formation is the "core-accretion" model, in which solid planetesimals of rock/ice composition accrete to form a massive protoplanetary core. When this core reaches a critical mass, of order $10M_{\oplus}$, it is able to capture gas from the solar nebula. Gas accretion is eventually terminated by dissipation of the nebula, tidal formation of a gap, and/or local depletion of the gas supply. At present, this model is more qualitative scenario than quantitative theory. Among the problems as yet unsolved are the timescale for accreting such a massive core within the relatively short lifetime ($\sim 10^7$ y) of the nebula, and the number of such cores that might result from stochastic accretion of planetesimals.

In a recent paper Pollack *et al.* (1996) attempt to build a more quantitative model of formation of giant planets. They start with a postulated Mars-sized "seed body" within a swarm of much smaller planetesimals. Using analytic arguments (Lissauer 1987), they find that such a body should experience "runaway growth," rapidly sweeping up the smaller bodies until the mass within a "feeding zone" is depleted. For the nebular parameters chosen (surface density of solid matter 10 g/cm^2 at 5.2 AU), the planetary embryo reaches a mass of $10M_{\oplus}$ in about 5×10^5 y before the runaway terminates. Later growth is slower, governed by orbital diffusion of more distant planetesimals from beyond the feeding zone. The energy released by accreted planetesimals controls the rate of gas accretion.

While the model of Pollack *et al.* is the most detailed and self-consistent produced to date, it does not justify adequately its initial conditions, e.g., the formation of the seed body (how does it get so much bigger than its neighbors?) and its uniqueness (why should there be only one in the region that eventually produces a Jupiter-sized planet?). Their analytic model of runaway growth also neglects interactions between the planetesimals, which are not allowed to grow. A realistic model should demonstrate that runaway growth of a protoplanetary core can occur without conferring an unfair advantage on the embryo.

Here I report on the first step of an effort to produce such a model, using the multizone planetary accretion code (Spaute *et al.* 1991, Weidenschilling *et al.* 1996) to model the growth process numerically. This approach should be able to simulate the formation of an embryo (or multiple embryos) by stochastic accretion of a population of small planetesimals. However, the present work addresses a simpler problem: given the initial conditions assumed by Pollack *et al.*, what is the timescale of runaway growth, and how large a core is produced?

The multizone simulation covers a region of width 1 AU, extending from 4.7 to 5.7 AU. This region is divided into a number of zones in semimajor axis; the number of zones used determines the width of each zone. The accretable solid matter has surface density 10 g/cm^2 at 5.2 AU, varying as a^{-2}. The planetesimals have radius 100 km (mass 5.8×10^{21} g), with $e = V_e/V_k$, $i = 0.6\,e$. The central zone contains a discrete body at 5.2 AU, with mass 6.4×10^{26} g at $t = 0$. To match the Pollack *et al.* model, I allow only the discrete body to grow by accretion; the planetesimals do not collide with each other. Gravitational stirring occurs between planetesimals, but the perturbations of the massive embryo are dominant. Gas (with density 5×10^{-11} g/cm^3) is present, causing a slight damping of planetesimal velocities on long timescales.

The gravitational stirring model used is from Wetherill and Stewart (1993). However, initial trials in this case produced too much stirring by the embryo. Stewart's continuum stirring model assumes a uniform spatial distribution of many perturbing bodies, a condition that is not met if the stirring is done by a single massive body. Conservation of the Jacobi parameter in encounters makes a large body less effective at stirring small ones. From the results of Greenzweig and Lissauer (1992), I limit the mean eccentricity excited by the embryo to twice its scaled Hill radius ($R_H = (m/3M_{\odot})^{1/3}$). Greenzweig and Lissauer also showed that a massive body is quite ineffective for out-of-plane perturbations, so the stirring rate of inclinations is limited to 0.01 times the rate for eccentricities.

I have computed the evolution of the planetesimal population as the embryo grows by runaway accretion. Because the random velocities remain low, encounters are dominated by Keplerian shear; planetesimals are preferentially accreted from zones on either side of the embryo's orbit. Planetesimals

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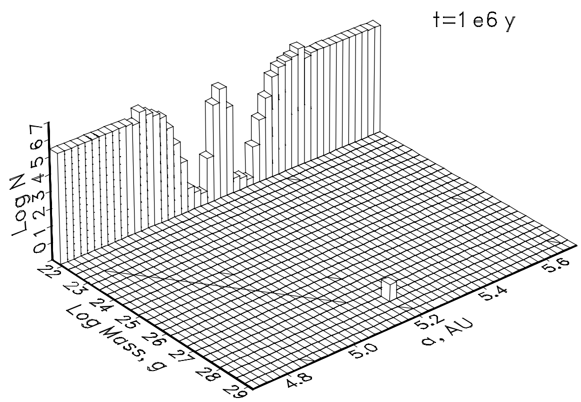
within ~R_H of the embryo's semimajor axis are trapped in horseshoe- or Trojan-type orbits. The other nearby zones are cleared effectively, but the growth takes 1-2x10^6 y, and stalls when the embryo mass reaches only about 2-3 Earth masses, rather than $10M_\oplus$ in 5x10^5 y. The principal reason for this difference appears to be their assumption that the planetesimals are well-mixed, i.e., always uniformly distributed across the embryo's feeding zone. In contrast, I find their surface density varies significantly; some bodies are in orbits with longer lifetimes. This behavior is seen in N-body integrations by Tanaka and Ida (1997). Also, a non-negligible fraction (~10%) of the population in the feeding zone is trapped in horseshoe or Trojan orbits. Moreover, conservation of the Jacobi parameter in encounters with the embryo causes stirring of velocities to be accompanied by changes in semimajor axes that move the planetesimals away from the embryo's orbit. When coupled with damping due to drag, the net result is a secular drift that can isolate the small bodies from the embryo (Tanaka and Ida 1997). This effect is seen in the simulations as an increase in surface density of planetesimals just beyond the zones depleted by accretion. The "well-mixed" assumption can be simulated by using the code at lower spatial resolution, with a few broad zones of width greater than the Hill radius of the final embryo. This approach yields a runaway core mass of order $10M_\oplus$, but this value is an artifact of the low resolution.

In summary, runaway growth of a potential core of a giant planet is less efficient than suggested by the analytic model, even when initial conditions give an overwhelming advantage (a factor 10^5 in mass!) to the embryo. Possible solutions to the formation problem include: 1) a higher nebular surface density to allow more extensive runaway, 2) competition of multiple embryos to reduce isolationist tendencies, or 3) migration of planetesimals by drag, or the embryo(s) by nebular gravitational torques (Ward 1995). These effects can be treated by the multizone code, and will be tested in the near future.



Number of planetesimals in zones of semimajor axis in the vicinity of the embryo after 10^6 y. The embryo has reached a mass of $2M_\oplus$ (diagonal lines in xy plane are artifacts of the plotting process).

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Supported by NASA Grant NAGW-4428.